

Autonomy Capability Development for a Titan Aerobot

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Exploration of the planets and moons of the Solar System has up to now relied on remote sensing from Earth, fly-by probes, orbiters, landers and rovers. Remote sensing probes and orbiters can only provide non-contact, limited resolution imagery over a small number of spectral bands; landers provide high-resolution imagery and in-situ data collection and analysis capabilities, but only for a single site; while rovers allow imagery collection and in-situ science across their path. The fundamental drawback of ground-based systems is limited coverage: in past or planned exploration missions, the rover range has varied from approximately 130m for the 1997 Sojourner mission, to currently 4.0 km for the Mars Exploration Rovers, to tens of kilometers for the teleoperated Lunokhod rovers.

There is currently a strategic gap in robotic exploration technologies for systems that combine extensive geographical coverage with high-resolution data collection and in-situ science capabilities. For planets and moons with an atmosphere, this gap can be addressed through aerial vehicles. In the Solar System, in addition to Earth, the planets Venus and Mars, the gas giants (Jupiter, Saturn, Uranus and Neptune) and the Saturn moon Titan have substantial atmospheres. Aerial vehicles that have been considered for planetary exploration include airplanes and gliders, helicopters, balloons [Kerzhanovich 2002] and airships. Flight time for gliders depends heavily on wind and updraft patterns, which in turn constrain their surface coverage, while airplanes and helicopters expend significant energy resources simply staying airborne [Elfes 2001, Elfes 2003].

Lighter-than-atmosphere (LTA) systems provide significant advantages for planetary exploration due to their potential for extended mission duration, long traverse, and extensive surface coverage capabilities. Robotic airships, in particular, are ideal platforms for airborne planetary exploration. Airships have modest power requirements, and combine the extended airborne capability of balloons with the maneuverability of airplanes or helicopters. Their controllability allows precise flight path execution for surveying purposes, long-range as well as close-up ground observations, station-keeping for long-term monitoring of high-value science sites, transportation and deployment of scientific instruments and in-situ laboratory facilities across vast distances to key science sites, and opportunistic flight path replanning in response to the detection of relevant science sensor signatures. Furthermore, robotic airships provide the ability to conduct extensive surveys over both solid terrain and liquid-covered areas, and to reconnoiter sites that are inaccessible to ground vehicles.

The main challenges for aerobot exploration of Titan include: *large communication latencies*, with a round trip light time of approximately 2.6 hours; *extended communication blackout periods* with a duration of up to 9 Earth days, caused by the rotation of Titan and its orbital occlusion by Saturn; *extended mission duration*, currently projected to be on the order of six months to one year; and *operation in substantially unknown environments*, with largely unknown wind patterns, meteorological conditions, and surface topography.

These challenges impose the following capability requirements on a Titan aerobot: *vehicle safing*, so that the safety and integrity of the aerobot can be ensured over the full duration of the mission and during extended communication blackouts; *accurate and robust autonomous flight control*, including deployment/lift-off, long traverses, hovering/station-keeping, and touch-and-go surface sampling; *spatial mapping and self-localization* in the absence of a global positioning system and probably of a magnetic field on Titan; and *advanced perceptual hazard and target recognition, tracking and servoing*, allowing the aerobot to detect and avoid atmospheric and topographic hazards, and also to identify, home in, and keep station over pre-defined science targets or terrain features.

In this paper, we present an aerobot autonomy architecture that integrates accurate and robust vehicle and flight trajectory control, perception-based state estimation, hazard detection and avoidance, vehicle health monitoring and reflexive safing actions, vision-based localization and mapping, and long-range mission planning and monitoring. We also discuss the development of a highly accurate aerodynamic airship model and its validation, as well as an initial implementation of the flight control system and the results obtained from autonomous flight tests conducted in the Mojave desert.